The Radiation Environment for Electronic Devices on the GOES-R Series Satellites

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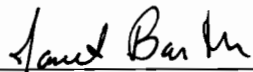
National Aeronautics and
Space Administration ———

Goddard Space Flight Center _____
Greenbelt, Maryland

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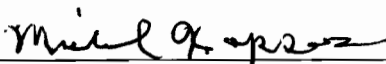
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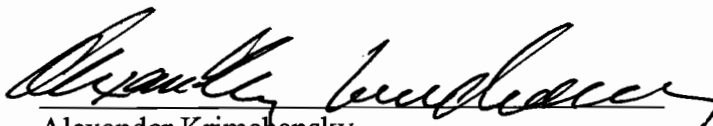Radiation Effects and Analysis Group/Code 561
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I. Introduction

The purpose of this document is to define the radiation environment for the evaluation of degradation due to total ionizing and non-ionizing dose and of single event effects (SEEs) for the GOES instruments and spacecraft. The analysis took into account the radiation exposure for the nominal 15-year mission (10 years operating & 5 years on-orbit storage) at geosynchronous orbit.

Orbit: Geosynchronous, H = 35790/35790 km, 15-year Mission Requirement including 10 years of operation and up to 5 years of on-orbit storage. On-orbit locations are 75 and 135 degrees W longitude. The storage position is 105 degrees W longitude.

The radiation environment effects that must be considered, and their level of severity for the GOES missions are listed in **Table 1**.

Table 1: Radiation Effects in Geosynchronous

Effect	Level of Severity
Spacecraft Charging/Discharging	Severe
Single Event Effects	Severe
Total Ionizing Dose	Moderate
Displacement Damage	Non-shielded (Solar Cells, Sensors) – Severe
	Shielded (Optoelectronics, Shielded Sensors) – Moderate

II. Radiation Environment

The natural space radiation environment of concern for damage to spacecraft electronics is classified into two populations, 1) the transient particles which include protons and heavier ions of all of the elements of the periodic table, and 2) the trapped particles which include protons, electrons and heavier ions. The trapped electrons have energies up to 10 MeV and the trapped protons and heavier ions have energies up to 100s of MeV. The transient radiation consists of galactic cosmic ray particles and particles from solar events (coronal mass ejections and flares). The cosmic rays have low-level fluxes with energies up to TeV. The solar eruptions periodically produce energetic protons, alpha particles, heavy ions, and electrons. The solar protons have energies up to 100's of MeV and the heavier ions reach the GeV range. All particle fluxes are isotropic and omnidirectional to the first order.

Space also contains low energy plasma of electrons and protons with fluxes up to 10^{12} cm^2/sec. The plasmasphere environment and the low energy (< 0.1 MeV) component of the charged particles are a concern in the near-earth environment. In the outer regions of the magnetosphere and in interplanetary space, the plasma is associated with the solar wind. Because of its low energy, thin layers of material

easily stop the plasma so it is not a hazard to most spacecraft electronics. However, it is damaging to surface materials and differentials in the plasma environment can contribute to spacecraft surface charging and discharging problems [1,2].

III. Description of Radiation Effects

Radiation effects that are important to consider for instrument and spacecraft design fall roughly into three categories: degradation from total ionizing dose (TID), degradation from displacement damage, and single event effects (SEEs).

A. Total Ionizing Dose

Total ionizing dose in electronics is a cumulative long term ionizing damage due to protons and electrons. It causes threshold shifts, leakage current and timing skews. The effect usually first appears as parametric degradation of the device and ultimately results in functional failure. It is possible to reduce TID with shielding material that absorbs most electrons and lower energy protons. As shielding is increased, shielding effectiveness decreases because of the difficulty in slowing down the higher energy protons. When a manufacturer advertises a part as "rad-hard", he is almost always referring to its total ionizing dose characteristics. Rad-hard does not usually imply that the part is hard to non-ionizing dose or single event effects.

B. Displacement Damage

Displacement damage is cumulative long-term non-ionizing damage due to protons, electrons, and neutrons. The particles produce defects in optical materials that result in charge transfer degradation. These defects affect the performance of optocouplers (often a component in power devices), solar cells, CCDs, and linear bipolar devices. The effectiveness of shielding depends on the location of the device. For example, coverglasses over solar cells reduce electron damage and proton damage by absorbing the low energy particles. Increasing shielding, however, is not usually effective for optoelectronic components because the high-energy protons penetrate the most feasible spacecraft electronic enclosures. For detectors in instruments it is necessary to understand the instrument geometry to determine the vulnerability to the environment.

C. Single Event Effects

Single event effects (SEE) occur as a result of charge being generated along the path of primary or secondary ionizing particles, and then being collected on circuit nodes and disrupting normal circuit response. In most cases, SEE are caused by heavier ions. However, for some devices, protons can induce SEE—in some cases through direct ionization by the proton, or, more commonly, by ionization by secondary particles produced in collisions between the proton and a nucleus in the device material. Some single event effects are non-destructive as in the case of single event upsets (SEUs), single event transients (SETs), multiple bit errors (MBEs), single event hard errors (SHEs), etc. Single event effects can also be destructive as in the case of single event latchups (SELs), single event gate ruptures (SEGRs), and single event burnouts (SEBs). The severity of the effect can range from noisy data to loss of the mission, depending on the type of effect and the criticality of the system in which it occurs. Shielding is not an effective mitigator for single event effects because they are induced by very penetrating high-energy particles. The preferred method for dealing with destructive failures is to use SEE-hard parts. When SEE-hard parts are not available, latchup protection circuitry is sometimes used in conjunction with failure mode analysis. However, this approach should be adopted cautiously, as even SEL events that do not result in device destruction have been

observed to cause latent damage to the part, which degrades subsequent reliability. For non-destructive effects, mitigation takes the form of error-detection and correction codes (EDACs), filtering circuitry, etc.

D. Relevant Space Radiation Environments

Total ionizing dose is caused primarily by protons and electrons trapped in the Van Allen belts and solar event protons. As electrons are slowed down, their interactions with orbital electrons of the shielding material produce a secondary photon radiation known as bremsstrahlung. Generally, the dose due to galactic cosmic ray ions and proton secondaries is negligible in the presence of the other sources. For surface degradation, it is also important to include the effects of very low energy particles.

Single event effects can be induced by heavy ions (solar events and galactic cosmic rays) and, in some devices, protons (trapped and solar events) and neutrons. Displacement damage is primarily due to trapped and solar protons and also neutrons that are produced by interactions of primary particles with the atmosphere and spacecraft materials.[*] For lightly shielded applications, such as solar arrays, displacement damage may also occur due to energetic trapped electrons. Spacecraft charging can occur on the surface of

the spacecraft due to low energy electrons. Deep dielectric charging occurs when high energy electrons penetrate the spacecraft and collect in dielectric materials.

IV. The GOES Mission

The GOES spacecraft will be launched out to a geosynchronous orbit via a trajectory that has not yet been defined. Once GOES is at its geosynchronous orbit, its mission requirement is 15 years, with 10 years operational at 135W or 75W longitude and 5 years parking at 105W longitude. Because of its lengthy timescale, the GOES mission will include satellites launched throughout the solar cycle. For this reason, it is prudent to assume that the mission will occur during during worst-case environmental conditions. In terms of TID, displacement damage and spacecraft charging threats, this is the active phase of the solar cycle. In terms of single-event effects, the appropriate galactic cosmic ray (GCR) environment to assume is that for solar minimum, since GCR fluxes are slightly higher for this portion of the solar cycle. During the active phase of the sun, the likelihood that the spacecraft will be exposed to particles from solar events (either solar flare or coronal mass ejections) increases significantly. Based on an average 11-year solar cycle, the GOES mission will encounter 11 years of solar active conditions. **Figure 1** shows a projection of the solar cycle during the GOES mission, it is based on the solar activity data of solar cycles 22 and 23. The geosynchronous radiation environment encountered by the GOES will consist of protons, electrons and heavier ions from solar events, galactic cosmic ray heavy ions, and solar wind plasma consisting of low energy protons, electrons, and heavier ions.

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[*] In avionics applications it is necessary to consider neutrons that are produced by interactions of primary particles with the atmosphere.

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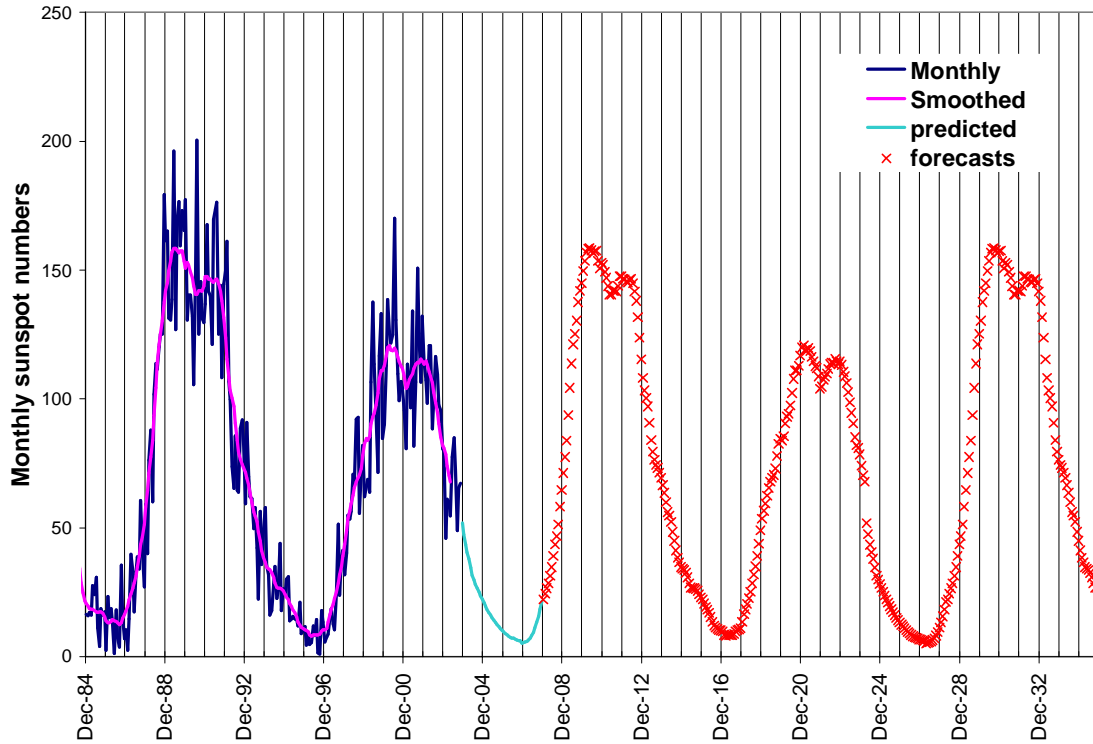
Figure 1: Projection of the solar activity during the GOES mission

V. Total Dose and Degradation Analysis

The total ionizing dose accumulation causes performance degradation and failure on memories, power converters, etc. Non-ionizing energy loss in materials (atomic displacement damage) causes degradation of solar cells, optoelectronics, and detectors. The low energy particles also contribute to the erosion of surfaces.

A. *Degradation Environments*

In geosynchronous orbits low energy particles (< 40 keV) from the solar wind plasma contribute to the degradation of surface materials. The higher energy particles trapped in the Van Allen belts and from high-energy solar events can penetrate solar cell cover glasses and solar array substrate structures and, therefore,

are responsible for solar cell degradation. Microelectronics components are also susceptible to high energy particles even though they are usually inside box enclosures.

1. The Plasma Environment [3]

The geosynchronous environment will charge spacecraft exterior surfaces. Since different materials are used and since sunlight can illuminate only one side at a time, there will always be some differential charging as well as absolute charging. The effect of this surface charging on the performance of spacecraft must be evaluated in terms of malfunctions, upsets and failures. Surface charging could disrupt environmental measurements on scientific spacecraft where control of electrostatic fields is required. For this reason, material selection to minimize differential charging is recommended. If the charging analysis indicates differential potentials of less than 500V, there should be no spacecraft discharge problems. However, if predicted potentials on materials exceeds 500V, the NASA Charging Analyzer Program (NASCAP) can be used. The worst-case geosynchronous plasma environment is given in **Table 2** and can be used as input to the NASCAP program.

Table 2: Worst-Case Geosynchronous Plasma Environment

Electron number density, N_E, cm^{-3}	1.12
Electron temperature, T_E, eV	1.2×10^4
Ion number density, N_I, cm^{-3}	2.36×10^{-1}
Ion temperature, T_I, eV	2.95×10^4

Surface charging also increases contamination. The contaminants are attracted back to charged surfaces and deposit on them. This changes the surface characteristics. Altered surface optical properties result in higher temperatures. Changes in secondary and photoelectron yields result in altered charging characteristics. Deposition of the dielectric contaminants can also reduce surface conductivity. If severe discharges were to occur on the surfaces, the materials can be damaged which can change their thermal control performance. **Table 3** lists the acceptable and unacceptable surface coatings and materials for spacecraft use.

Table 3: Surface Coatings and Materials

Acceptable Material/Coating	Unacceptable Material/Coating
Paint(carbon black)	Anodyze
GSFC NS43 paint(yellow)	Fiberglass material
Indium tin oxide	Paint(white)
Zinc ortho-titanate paint(white)	Mylar(uncoated)
Alodyne	Teflon(uncoated)
	Kapton(uncoated)
	Silica cloth
	Quartz and glass surfaces(if possible to avoid)

2. High Energy Particles – Spacecraft Incident Fluences

The spacecraft incident proton fluence levels given in this document are most often used for standard solar cell analyses that take into account the coverglass thickness of the cell. There are two possible sources of high-energy particles: trapped electrons encountered in the geosynchronous orbit and protons from solar events that can occur anytime during the 15 years of the mission. The proton fluence levels are also used to determine displacement damage effects, however, most analysis methods require that the surface incident particles be transported through the materials surrounding the sensitive components. The proton fluences behind nominal aluminum shield thicknesses are given in Section V.A.3.

The trapped particle fluxes were estimated with NASA's AP-8 [4] model for protons and AE-8 [5] model for electrons. The models come in solar minimum and maximum versions. The uncertainty factors defined for the models are a factor of 2 for the AP-8 and 2 to 5 for the AE-8. These uncertainty factors apply to long-term averages expected over a 6-month mission duration. Daily values can fluctuate by two to three orders of magnitude depending on the level of activity on the sun and within the magnetosphere.

The solar proton levels can now be estimated from the new Emission of Solar Proton (ESP) model [6]. Previously, estimates of solar proton levels were obtained from models [7,8] that were largely empirical in nature, making it difficult to add data to the model from more recent solar cycles. The ESP model is based on satellite data from solar cycles 20, 21, and 22. The distribution of the fluences for the events is obtained from maximum entropy theory, and design limits in the worst case models are obtained from extreme value theory. The solar proton predictions are not linear over time; therefore, the levels given in this document may be invalid if extrapolated for longer mission durations.

Total integral solar proton fluences were estimated for a 15-year mission with 11 of those years being solar active years. **Table A1** gives the proton fluence levels as a function of particle energy for 90% & 95% confidence levels for a 15-year mission involving 11 solar active years. **Table A2** gives the electron fluence levels as a function of particle energy for the following: 10 years at 75°W, 5 years at 105°W, 10 years at 135°W, 15 years (10 years at 75°W & 5 years at 105°W) and the worst case of 15 years (10 years at 135°W & 5 years at 105°W). **Figure 2** is a plot of the data contained in **Table A1** and **Figure 3** is a plot of the data contained in **Table A2**. The energies are in units of >MeV and the fluences are in units of particles/cm^2. These values do not include a design margin.
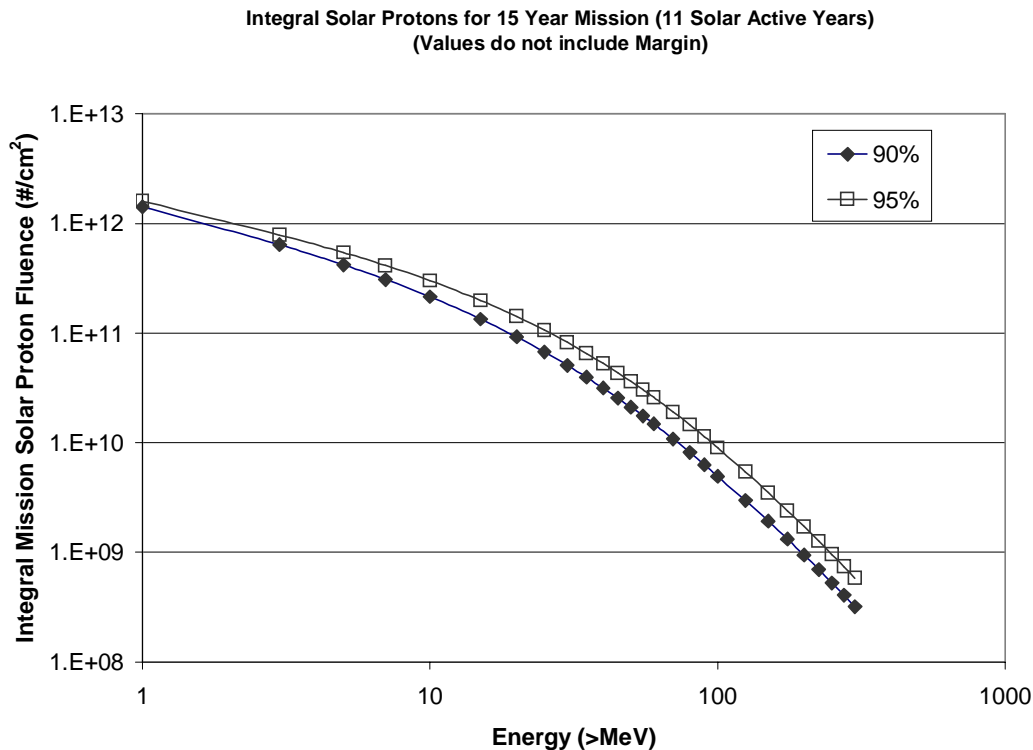
Figure 2: Integral solar proton fluences for 15-year mission involving 11 solar active years are presented for 90% & 95% confidence levels.

Integral Electron Fluences for GOES Mission
(Values do not include margins)
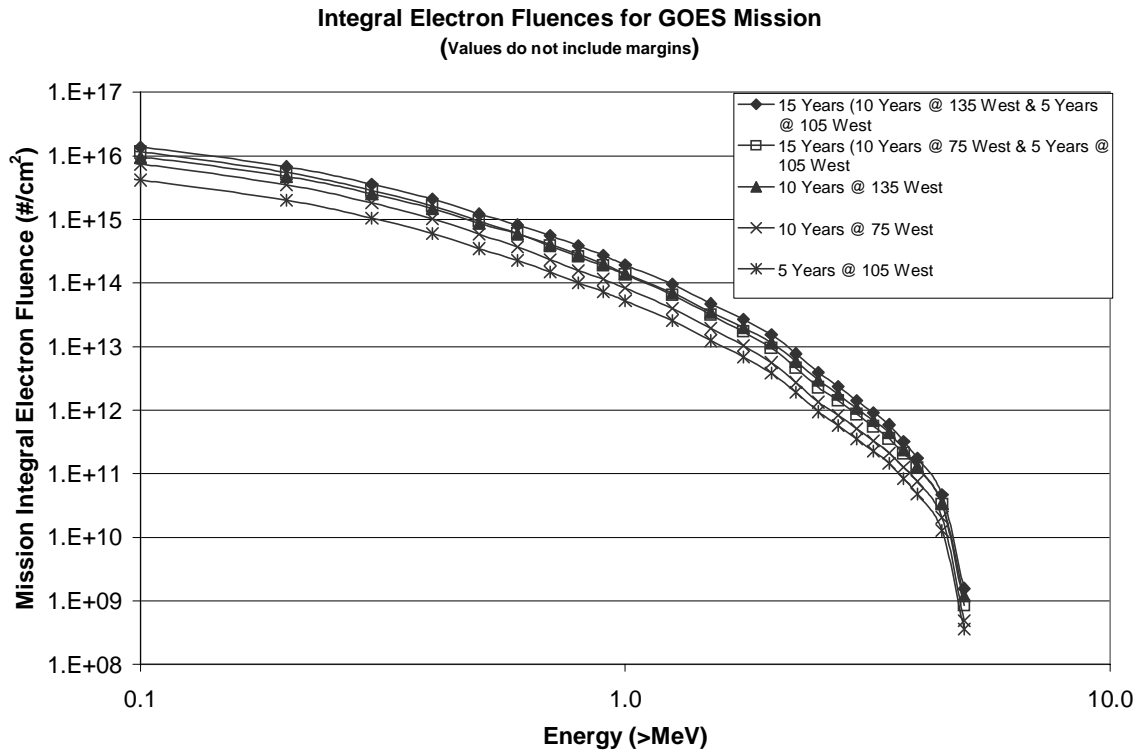
Figure 3: Integral electron fluences for GOES mission.

3. High Energy Particles – Shielded Fluences

Evaluation of non-ionizing energy loss damage requires the use of shielded fluence levels. For this analysis nominal shielding thicknesses of 50, 100, 200, 350 and 500 mils of aluminum were used for a generic solid sphere geometry. The spacecraft incident, solar proton estimates for the 90% confidence level for 15-year mission duration with 11 year solar active years were transported through the shield thickness to obtain fluence estimates behind the shielding. **Table A3** gives the degraded proton energy spectra. The spectra are plotted in **Figure 4**. The electron fluence estimates behind these shields for the 15-year worst-case mission (10 years at 135°W & 5 years at 105°W) are given in **Table A4** and plotted in **Figure 5**. The electron fluence estimates behind these shields for the other 15-year mission scenario (10 years at 75°W & 5 years at 105°W) are given in **Table A5** and plotted in **Figure 6**. It can be seen from the figures that even

though the shielding absorbs low energy particles, the low energy range of the spectrum is filled in by the higher energy particles as they are degraded by passing through the material.

Shielded Integral Solar Proton Fluences for 15 Year Mission
With 11 Solar Active Years @ 90% Confidence Level
(Values do not include margins)
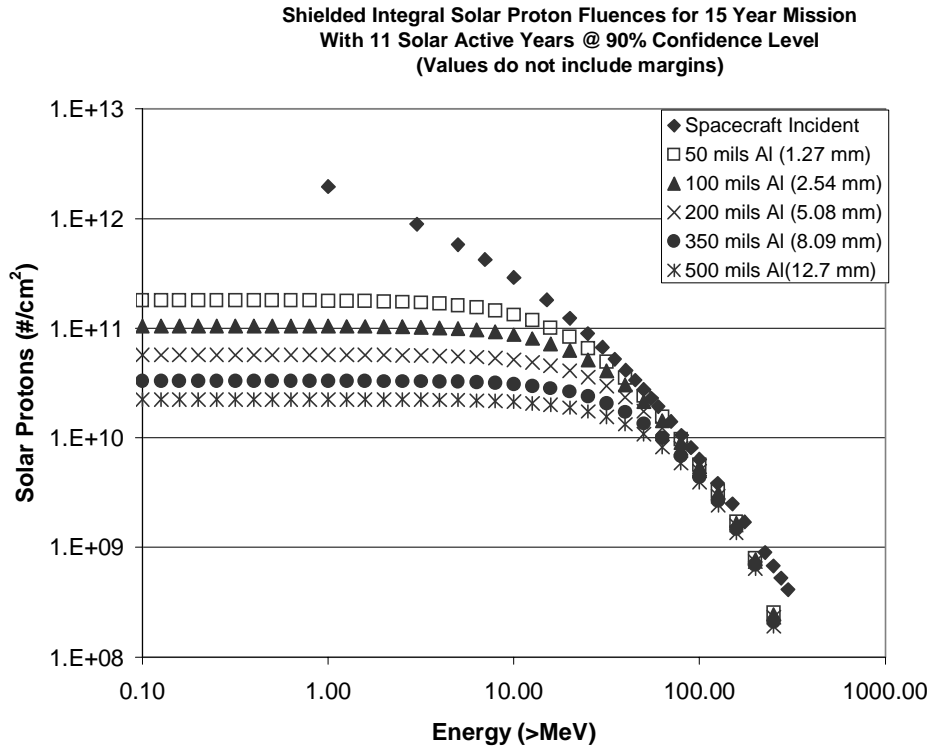
Figure 4: Shielded integral solar proton fluences for 15 years with 11 solar active years (90% confidence level).

Shielded Integral Electron Fluences for 15 Year Mission (Worst Case)
10 Years @ 135 W & 5 Years @ 105 W
(Values do not include margins.)
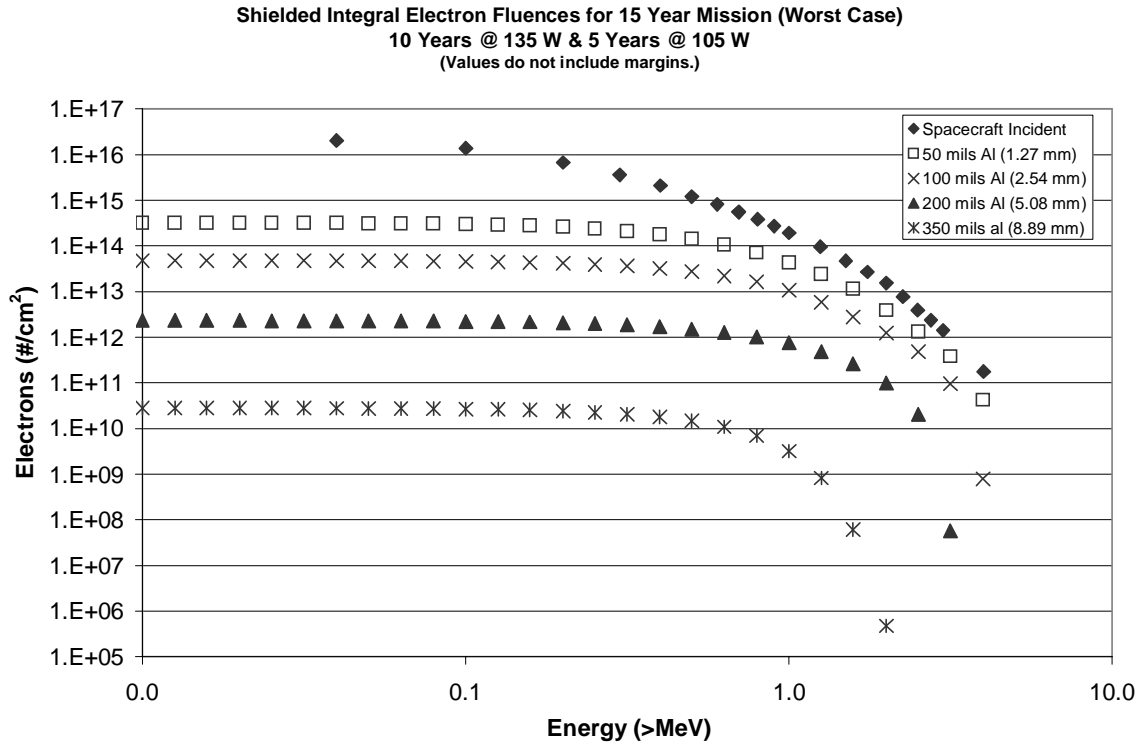
Figure 5: Shielded Integral Electron Fluences For 15 Year Mission (Worst Case).

Shielded Integral Electron Fluences for 15 Year Mission
10 Years @ 75° West & 5 Years @ 105° West
(Values do not include margins.)
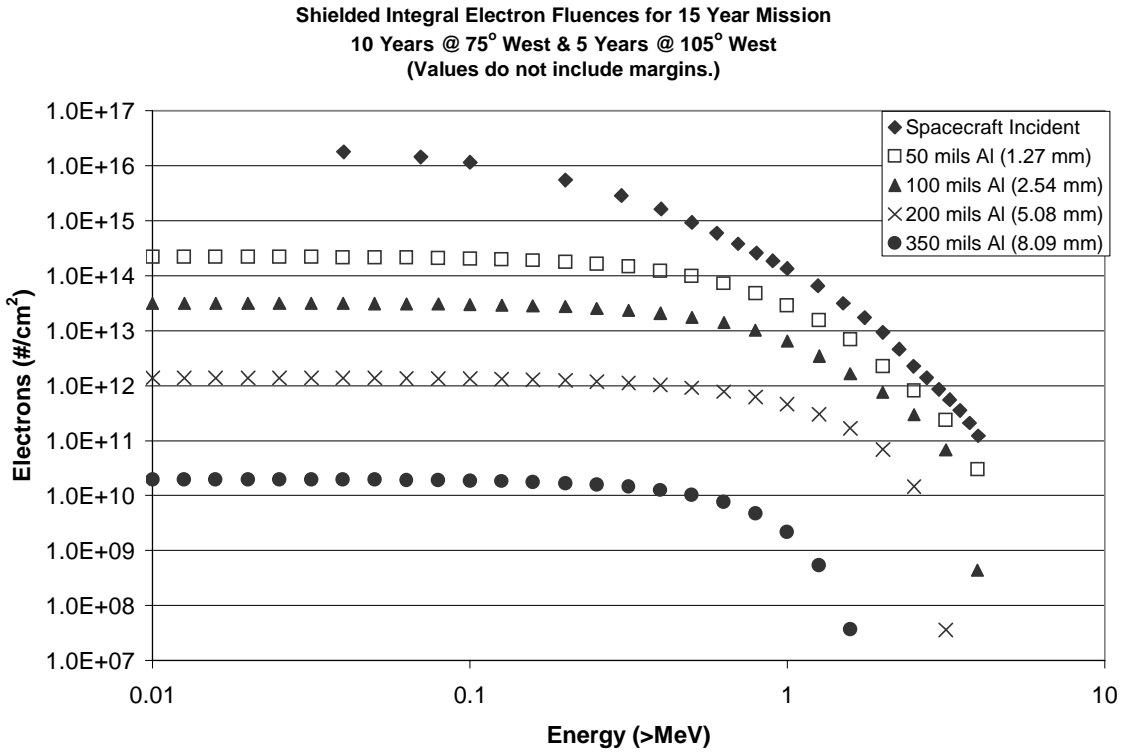
Figure 6: Shielded Integral Electron Fluences For 15 Year Mission.

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B. *Total Dose Estimates*

1. Top Level Ionizing Dose Estimates

Doses are calculated from the surface incident integral fluences as a function of aluminum shield thickness for a simple geometry. The geometry model used for spacecraft applications is the solid sphere. The solid sphere doses represent an upper boundary for the dose inside an actual spacecraft and are used as a top-level requirement. In cases where the amount of shielding surrounding a sensitive location is difficult to estimate, a more detailed analysis of the geometry of the spacecraft structure may be necessary to evaluate the expected dose levels. This is done by modeling the electronic boxes or instruments and the spacecraft structure. The amount of shielding surrounding selected sensitive locations is estimated using solid angle sectoring and 3-dimensional ray tracing. Doses obtained by sectoring methods must be verified for 5-10% of the sensitive locations with full Monte Carlo simulations of particle trajectories through the structure for many histories.

Table A6 and **Figure 7** give the top-level total ionizing dose results for the worst-case 15-year GOES mission (10 years at 135°W and 5 years at 105°W). **Table A7** and **Figure 8** give the top-level total ionizing dose results for the other 15-year GOES mission scenario (10 years at 75°W and 5 years at 105°W). The solar proton doses were calculated using 11 solar active years and a 90% confidence level. The doses (rads silicon) are calculated here as a function of aluminum shield thickness for solid spheres. A minimum design margin of x 2 is recommended.
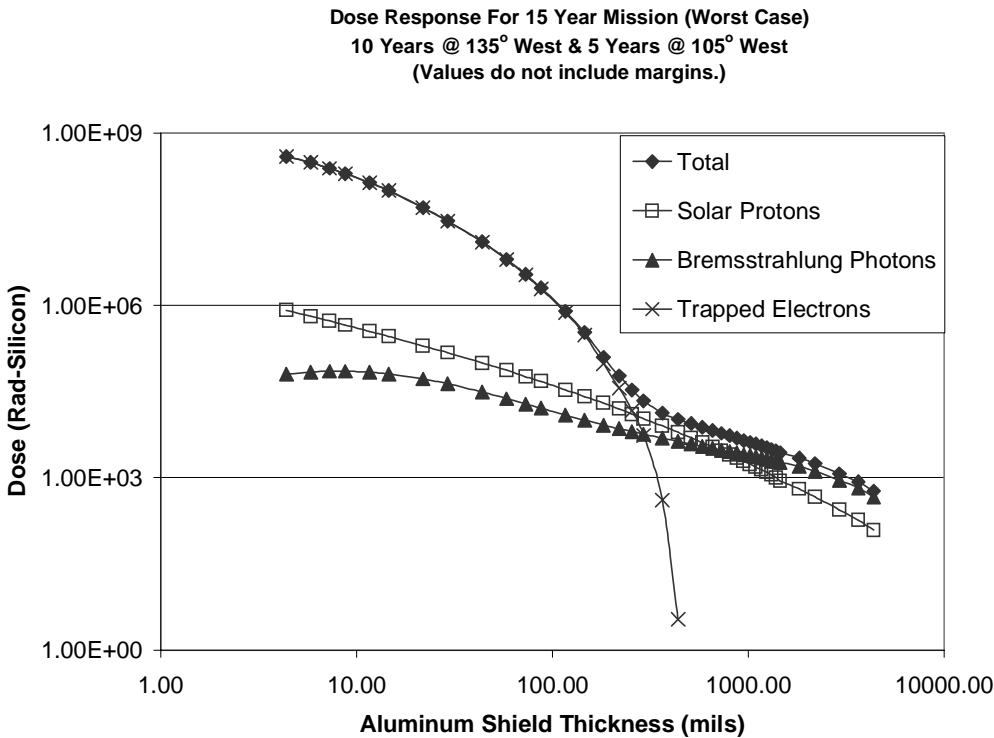
Figure 7: Total ionizing dose for 15 year mission (worst case).

Dose Response For 15 Year Mission
10 Years @ 75° West & 5 Years @ 105° West
(Values do not include margins.)
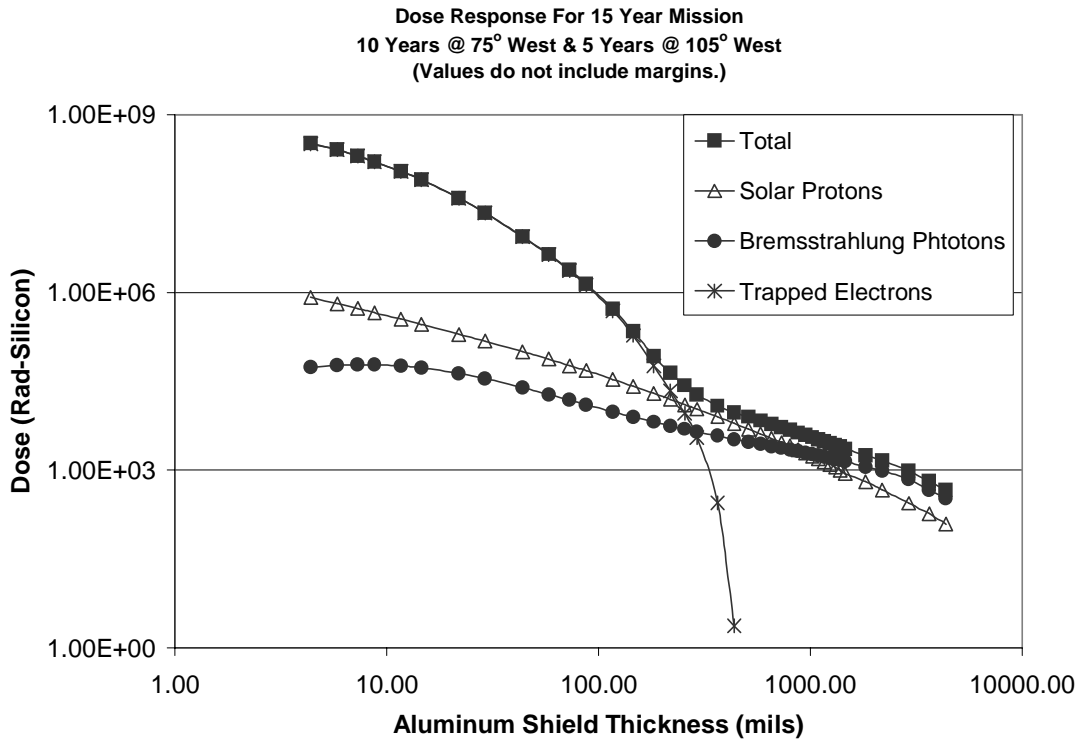
Figure 8: Total ionizing dose for 15 year mission.

2. Dose at Specific Spacecraft Locations

In cases where parts cannot meet the top level design requirement and a "harder" part cannot be substituted, it is often beneficial to employ more accurate methods of determining the dose exposure for some spacecraft components to qualify the parts. One such method for calculating total dose, solid angle sectoring/3-dimensional ray tracing, is accomplished in three steps:

1) Model the spacecraft structure:
   -develop a 3-D model of the spacecraft structures and components
   -develop a material library
   -define sensitive locations
2) Model the radiation environment:
   -define the spacecraft incident radiation environment

   -develop a particle attenuation model using theoretical shielding configurations
     (similar to dose-depth curves).
3) Obtain results for each sensitive location:
   -divide the structural model into solid angle sectors
   -ray trace through the sectors to calculate the material mass distribution
   -use the ray trace results to calculate total doses from the particle attenuation model.

Once the basic structural model has been defined, total doses can be obtained for any location in the spacecraft in a short time (in comparison to Monte Carlo methods). The value of dose mitigation measures can be accurately evaluated by adding the changes to the model and recalculating the total dose. For spacecraft with strict weight budgets, the 3-D ray trace method, the total dose design requirement can be defined at a box or instrument level avoiding unnecessary use of expensive or increasingly unavailable radiation hardened parts.

As the design of the GOES evolves, it may become necessary to estimate the doses at specific locations in the spacecraft or instruments. Often the dose requirement can be met by modeling the surrounding electronic box only or by modeling only the instrument.

C. *Displacement Damage Estimates*

Long-term damage due to atomic displacements (displacement damage) degrades solar cells, optoelectronics, imaging devices such as CCDs, and some bipolar technologies. The displacement damage is caused by exposure of the components to protons and electrons. In the geosynchronous environment, the threat ranges from moderate to severe depending on the amount of shielding surrounding the components. Sensors that are fully exposed to the space environment are especially susceptible.

Displacement damage is evaluated by combining the shielded proton energy spectra given in Section V.A.3 for the material and the results of laboratory irradiation of the devices sensitive to atomic displacement damage. The level of the hazard is highly dependent on the device type and can be process specific. For the GOES mission, it is important to keep in mind that some optoelectronic devices experience enough damage during one large solar proton event to cause the device to fail. It is necessary that the parts list screening for radiation also include a check for devices that are susceptible to displacement damage.

This document does not address solar array degradation due to the space radiation environment. However, the material that is described in the JPL Publication 96-9 titled "GaAs Solar Cell Radiation Handbook"[9], dated July 1, 1996, contains useful material that can be used by the spacecraft contractor as a guide when preparing his solar array degradation model.

VI. Single Event Effects Analysis

A. *Heavy Ion Induced Single Event Effects*

Some electronic devices are susceptible to single event effects (SEEs), e.g., single event upsets, single event latch-up, single event burn-out. Because of their ability to penetrate to the sensitive regions of devices and their ability to ionize materials, heavy ions cause SEEs by the direct deposit of charge. The quantity most frequently used to measure an ion's ability to deposit charge in devices is linear energy transfer (LET). Heavy ion abundances are converted to total LET spectra. Once specific parts are selected for the mission and, if necessary, characterized by laboratory testing, the LET spectra for the heavy ions are integrated with the device characterization to calculate SEE rates. Heavy ion populations that have sufficient numbers to be a SEE hazard are the galactic cosmic rays and those from solar events.

1. Galactic Cosmic Rays

The cosmic ray fluxes for elements hydrogen through uranium were used to calculate daily LET spectra for 100 mils nominal aluminum shielding as given in **Table A8** and **Figure 9**. The range of the cosmic ray abundances is bounded by the extremea of the solar active and inactive phases of the solar cycle with the highest values occurring during the solar inactive phase and the lowest during the solar active phase. With the extended mission goal of 15 years, the highest values should be used for single event effects analyses. The LET fluence values are given for the highest and lowest point of the solar cycle. The CREME96 [10] model was used to obtain the cosmic ray heavy ion abundances. This model has an accuracy of 25-40%.

Integral LET Spectra at 1AU (Z=1-92) for Interplanetary Galactic Cosmic Rays
100 mils Aluminum Shielding, CREME96
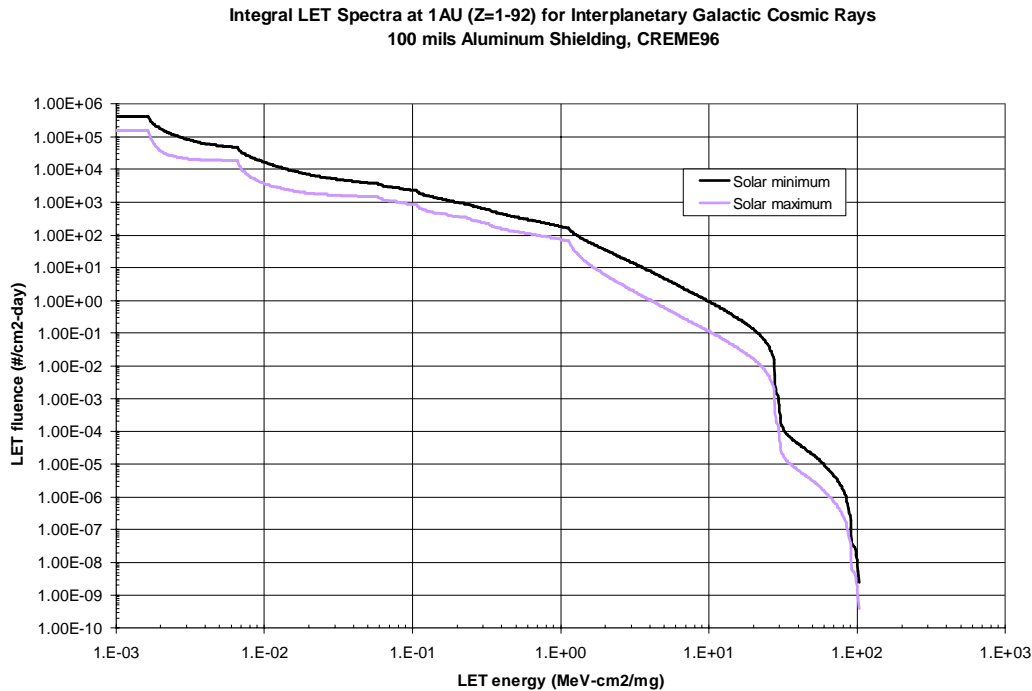
Figure 9: Integral LET spectra are shown for galactic cosmic ray ions hydrogen through uranium.

2. Solar Heavy Ions

The heavy ions from solar flares and coronal mass ejections can also produce single event effects. The solar event fluxes for the elements hydrogen through uranium were used to calculate daily LET spectra for 100 mils nominal aluminum shielding in units of average LET flux per second. The intensity of the fluxes varies over the duration of an event; therefore, values are averaged over the worst week of the solar cycle, the worst day of the solar cycle, and the peak of the October 1989 solar event. **Table A9** and **Figure 10** give the solar heavy ion LET predictions for the GOES mission. The CREME96 model was also used to calculate the solar heavy ion levels. An uncertainty factor for the solar heavy ion model has not been released.

Integral LET Spectra at 1 AU (Z=1-92) for Interplanetary Solar Particle Events
100 mils Aluminum Shielding, CREME96
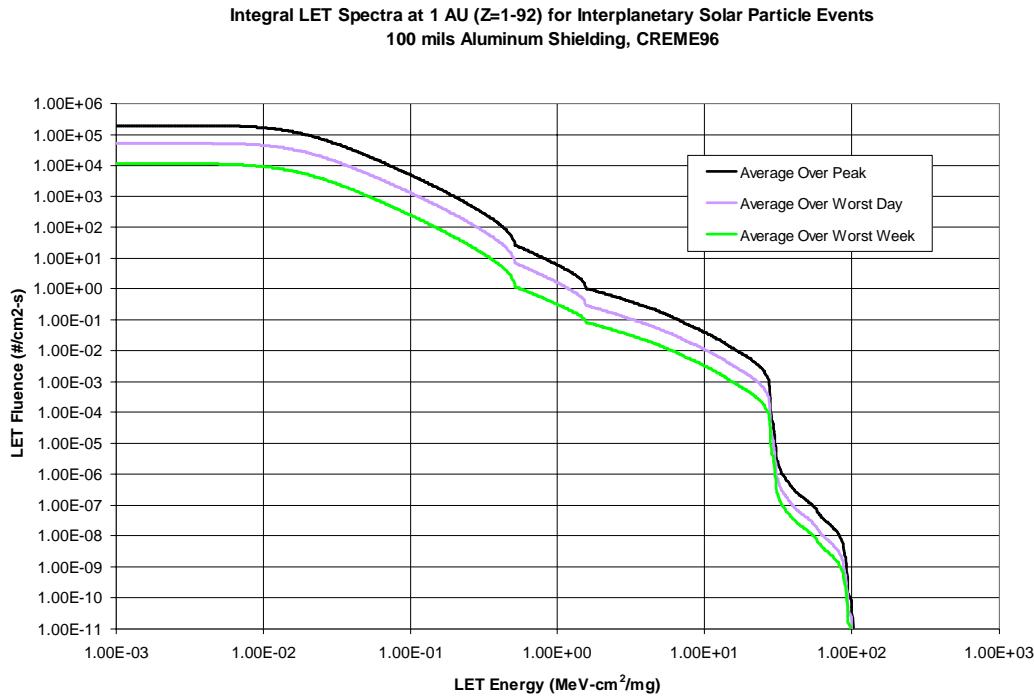
Figure 10: Integral LET spectra are shown for hydrogen through uranium for the October 1989 solar particle event.

B. *Proton Induced Single Event Effects*

In some devices, single event effects are also induced by protons. Protons from the trapped radiation belts and from solar events do not generate sufficient ionization (LET < 1 MeV-cm^2/mg) to produce the critical charge necessary for SEEs to occur in most electronics. More typically, protons cause Single Event Effects through secondary particles via nuclear interactions, that is, spallation and fractionation products. Because the proton energy is important in the production (and not the LET) of the secondary particles that cause the SEEs, device sensitivity to these particles is typically expressed as a function of proton energy rather than LET.

1. Trapped Protons

At geosynchronous orbit, the trapped protons have energies < 2 MeV. Therefore, they are not a significant factor in producing interference or damage in microelectronics.

2. Solar Protons

Protons from solar events will also be a single event effects hazard for the GOES spacecraft. These enhanced levels of protons could occur anytime during the 15-year mission but are most likely during the portion of the mission that occurs during the active phase of the solar cycle. As with the solar heavy ion LET spectra, solar proton fluxes are averaged over worst day, worst week, and the peak of the October 1989 solar event. The proton flux averages for a nominal 100 mils of shielding are given in **Table A10** and are shown in **Figure 11**.

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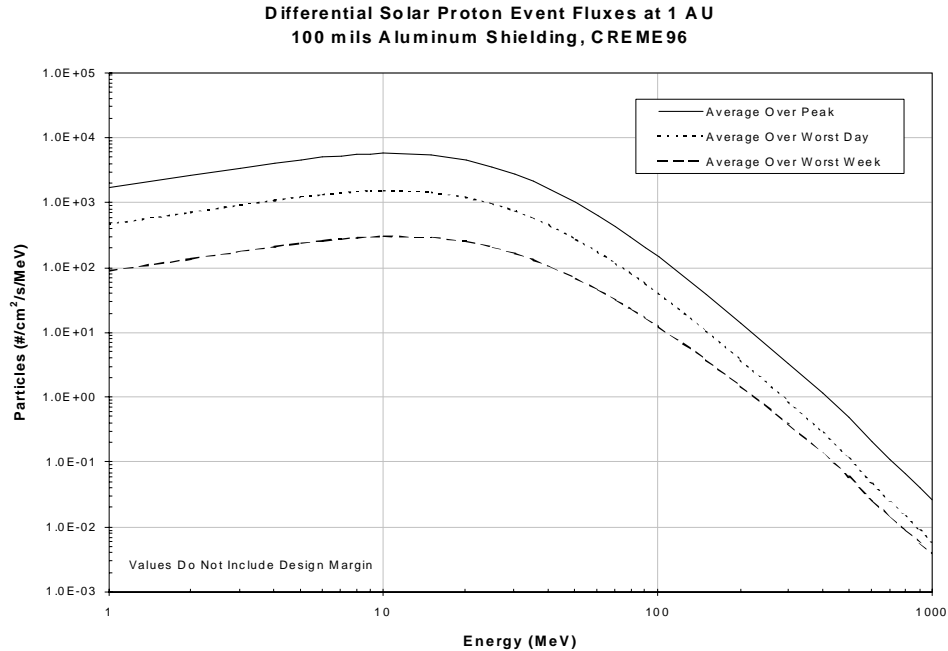
Figure 11: Solar proton fluxes for single event effects evaluation.

VII. Instrument Interference

The particle background causes increased noise levels in instruments and other electronics. This can be a concern if low noise levels are required for instrument observations, for example. The particle background of concern in GEO comes from galactic cosmic rays, trapped electrons, and solar particle events. The galactic cosmic ray background is fairly steady and varies slowly with the solar cycle. The trapped electron environment is very volatile at GEO altitudes and the electron fluxes can vary by several orders of

magnitude over periods as short as a month. Solar particle events typically last from days to weeks. The particle fluxes during these events vary continuously with time and can reach values that are comparable to trapped electron fluxes. Both long-term and worst-case estimates of these particle fluxes are given in **Table 4** for a nominal shielding of 100 mils of aluminum.

Table 4: Long-term and worst-case particle fluxes in GEO behind 100 mils of aluminum shielding

Radiation:	Long-term flux ($\#/cm^2/s$):	Worst-case flux ($\#/cm^2/s$):
galactic cosmic rays	2.5	4.6
trapped electrons	6.7×10^4	1.3×10^6
solar particle events	---	2.0×10^5

No long-term flux is included for solar particle events because the events occur over short periods of time compared to the length of the mission. Such a long-term flux would have little relevance for the viewing and data collection activities on GOES. However, particle interference during solar events is of particular concern because it can impact the observation times of instruments. To present a more realistic picture of the solar particle event flux variations, solar proton flux data from the Space Environment Monitor (SEM) of GOES are presented in **Figures 12-14**. The elemental composition of a solar particle event consists of about 95% protons, on average. These

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figures represent the hourly average flux of >50 MeV protons as a function of time for the years 1989, 1990 and 1991. This was a very active period during the solar maximum phase of the last complete solar cycle, #22. Note that the scale for flux in these figures is logarithmic.

Hourly Average of Solar Proton Flux > 50 MeV for 1989
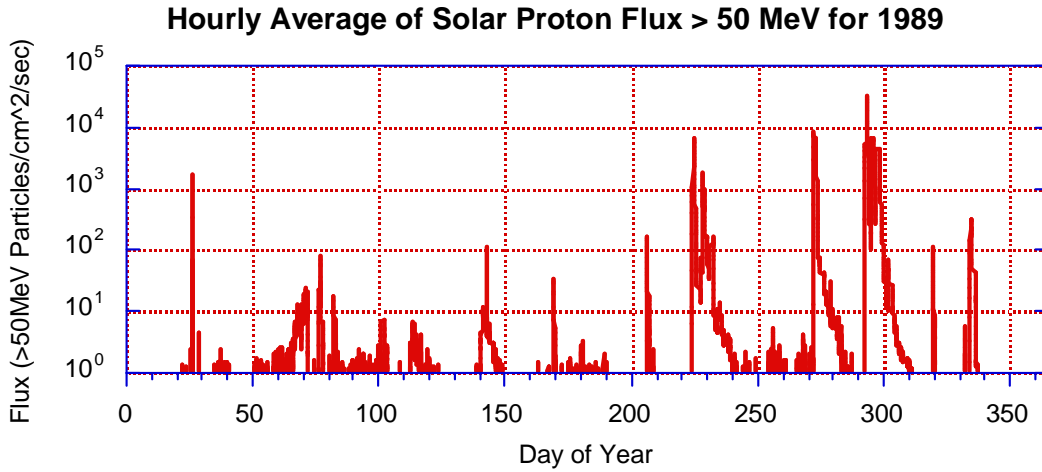
GOES Space Environment Monitor Data

Figure 12: Hourly averages of solar proton fluxes for > 50 MeV protons for 1989.

Hourly Average of Solar Proton Flux > 50 MeV for 1990
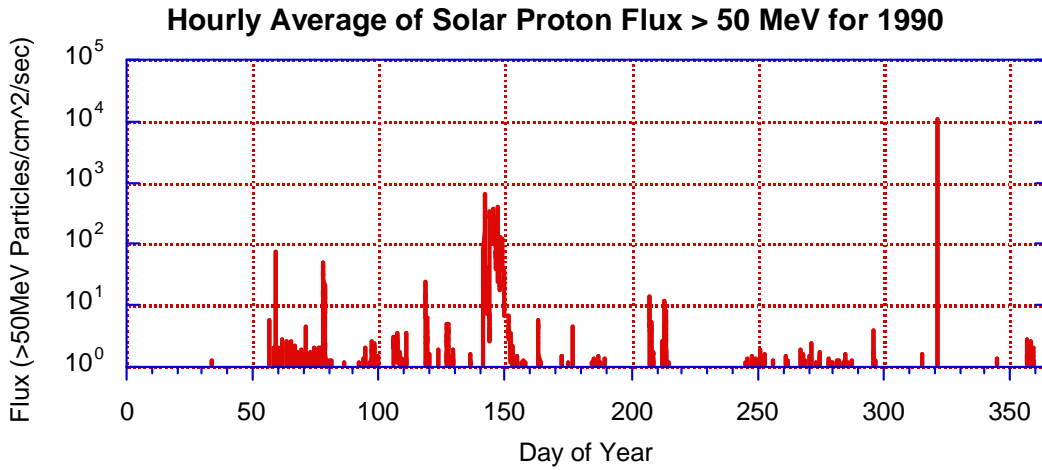
GOES Space Environment Monitor Data

Figure 13: Hourly averages of solar proton fluxes for > 50 MeV protons for 1990.

Hourly Average of Solar Proton Flux > 50 MeV for 1991
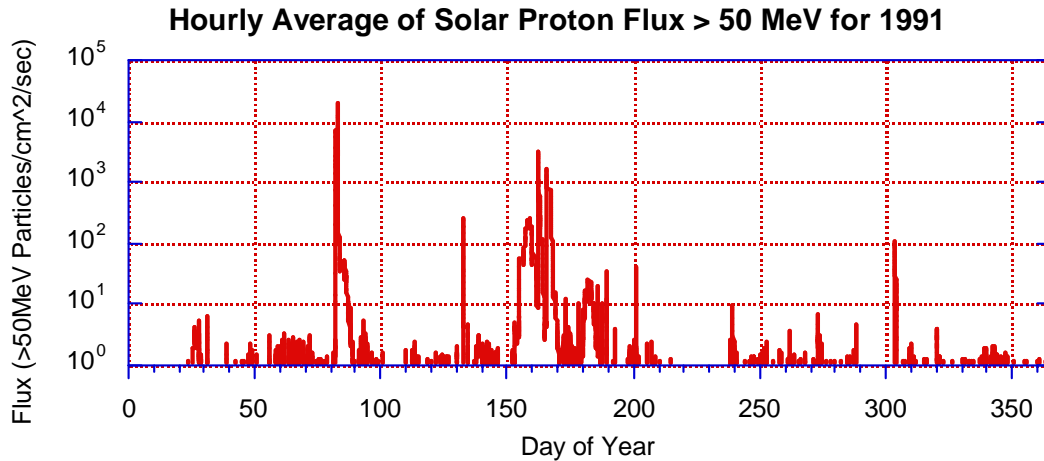
GOES Space Environment Monitor Data

Figure 14: Hourly averages of solar proton fluxes for > 50 MeV protons for 1991.

VIII. Spacecraft Charging and Discharging

Surface charging and deep dielectric charging must also be evaluated for the GOES mission. The spacecraft can accumulate high levels of electron build-up on spacecraft surfaces (low energy electrons) and in the dielectrics (high energy electrons). The particle accumulation profiles must be analyzed for possible surface and deep dielectric charging effects. The average electron accumulation profiles on a daily basis are shown in **Figure 15**. However, it should be remembered that these are long-term, average fluxes predicted by the AE8 Model and that on a given day the electron flux may be substantially higher. Measurements made on the GOES satellites indicate that daily flux levels can exceed those predicted by AE8 by a factor of about 20. When the transfer trajectory for the GOES spacecraft is defined, it also needs to be evaluated for levels of charging environments. The transfer trajectory will likely have a higher charging environment than at geostationary because of possible trajectory passes through more intense regions of the outer zone electron belt. Guidelines for controlling surface charging effects are given in reference [3] and guidelines for controlling deep dielectric charging are given in reference [11].
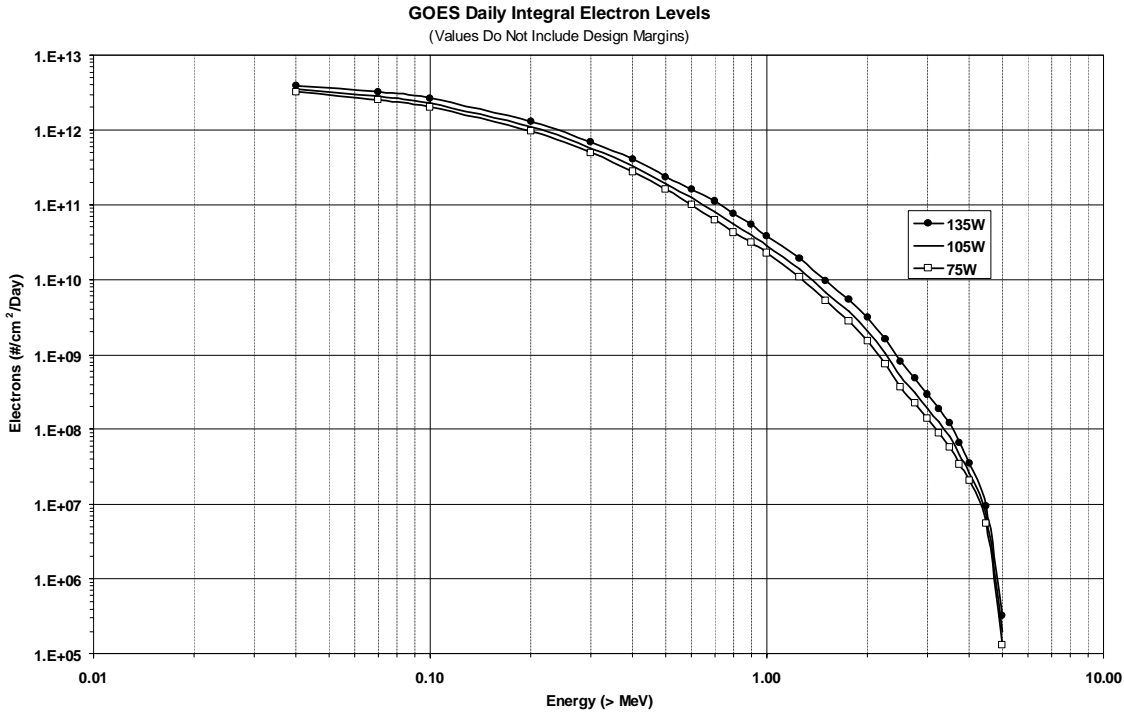
Figure1

5: **Daily integral electron levels for GOES.**

IX.   Summary

A top-level radiation environment specification was presented for the GOES mission. Although the environment is considered "moderate", the environment poses challenges to mission designers because of its highly variable nature caused by activity on the sun.

Spacecraft and instrument designers must be made aware that some newer technologies and commercial-off-the-shelf (COTS) devices are very soft to radiation effects. COTS devices that lose functionality at 5 krads of dose are not uncommon. Also, one extremely large solar proton event can cause enough displacement damage degradation in some optocoupler devices to cause failure. Increasingly, single event effects require careful part selection and mitigation schemes. With its full exposure to galactic cosmic heavy ions and particles from solar events, GOES must   have   a   carefully   planned   radiation   engineering   program.

X. References

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Appendices

Table A1

Spacecraft Incident Integral Solar Proton Fluences (#/cm^2) for 15 Year Mission (11 Solar Active Years)

Values Do Not Include Design Margins

Energy	Confidence	
>MeV	90%	95%
1	1.42E+12	1.60E+12
3	6.39E+11	7.85E+11
5	4.19E+11	5.43E+11
7	3.08E+11	4.14E+11
10	2.15E+11	3.01E+11
15	1.34E+11	1.98E+11
20	9.23E+10	1.42E+11
25	6.72E+10	1.06E+11
30	5.09E+10	8.21E+10
35	3.96E+10	6.52E+10
40	3.15E+10	5.28E+10
45	2.56E+10	4.33E+10
50	2.10E+10	3.62E+10
55	1.76E+10	3.04E+10
60	1.49E+10	2.59E+10
70	1.08E+10	1.91E+10
80	8.15E+09	1.46E+10
90	6.28E+09	1.13E+10
100	4.94E+09	8.98E+09
125	2.97E+09	5.42E+09
150	1.93E+09	3.51E+09
175	1.32E+09	2.39E+09
200	9.43E+08	1.72E+09
225	6.96E+08	1.27E+09
250	5.25E+08	9.57E+08
275	4.06E+08	7.38E+08
300	3.19E+08	5.80E+08

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Table A2
Spacecraft Incident Integral Electron Fluences (#/cm^2) for GOES Mission
Values Do Not Include Design Margins

Energy (>MeV)	10yrs at 135W + 5yrs at 105W	10 yrs at 75W + 5yrs at 105W	10 yrs at 135W	5yrs at 105W	10 yrs at 75W
0.04	2.05E+16	1.80E+16	1.41E+16	6.33E+15	1.17E+16
0.07	1.68E+16	1.44E+16	1.16E+16	5.12E+15	9.31E+15
0.10	1.38E+16	1.16E+16	9.60E+15	4.15E+15	7.43E+15
0.20	6.72E+15	5.49E+15	4.73E+15	1.99E+15	3.50E+15
0.30	3.59E+15	2.86E+15	2.54E+15	1.05E+15	1.81E+15
0.40	2.09E+15	1.63E+15	1.49E+15	6.02E+14	1.03E+15
0.50	1.21E+15	9.29E+14	8.67E+14	3.46E+14	5.83E+14
0.60	8.19E+14	5.95E+14	5.93E+14	2.26E+14	3.69E+14
0.70	5.54E+14	3.81E+14	4.06E+14	1.48E+14	2.33E+14
0.80	3.84E+14	2.58E+14	2.83E+14	1.01E+14	1.57E+14
0.90	2.73E+14	1.87E+14	2.00E+14	7.27E+13	1.15E+14
1.00	1.93E+14	1.36E+14	1.41E+14	5.23E+13	8.33E+13
1.25	9.58E+13	6.55E+13	7.03E+13	2.55E+13	4.00E+13
1.50	4.74E+13	3.15E+13	3.50E+13	1.24E+13	1.91E+13
1.75	2.69E+13	1.72E+13	2.00E+13	6.87E+12	1.03E+13
2.00	1.53E+13	9.40E+12	1.15E+13	3.81E+12	5.59E+12
2.25	7.73E+12	4.62E+12	5.84E+12	1.89E+12	2.73E+12
2.50	3.93E+12	2.27E+12	2.99E+12	9.41E+11	1.33E+12
2.75	2.34E+12	1.40E+12	1.77E+12	5.73E+11	8.24E+11
3.00	1.41E+12	8.59E+11	1.06E+12	3.49E+11	5.10E+11
3.25	9.11E+11	5.54E+11	6.86E+11	2.25E+11	3.29E+11
3.50	5.88E+11	3.56E+11	4.43E+11	1.45E+11	2.11E+11
3.75	3.22E+11	2.09E+11	2.39E+11	8.31E+10	1.26E+11
4.00	1.77E+11	1.23E+11	1.29E+11	4.75E+10	7.54E+10
4.50	4.67E+10	3.31E+10	3.40E+10	1.27E+10	2.04E+10
5.00	1.56E+09	8.40E+08	1.20E+09	3.59E+08	4.81E+08

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Table A3
Integral Solar Proton Fluences (#/cm^2) Behind Solid Sphere Aluminum Shields
15 Year Mission (11 Active Solar Years) – 90% Confidence Level
Values Do Not Include Design Margins

Degraded Energy	Shielded Solar Proton Fluences				
	50 mils Al (1.27 mm)	100 mils Al (2.54 mm)	200 mils Al (5.08 mm)	350 mils Al (8.89 mm)	500 mils Al (12.7 mm)
> MeV	#/cm^2	#/cm^2	#/cm^2	#/cm^2	#/cm^2
0.100	1.33E+11	7.88E+10	4.35E+10	2.52E+10	1.72E+10
0.126	1.33E+11	7.88E+10	4.35E+10	2.52E+10	1.72E+10
0.158	1.33E+11	7.88E+10	4.35E+10	2.52E+10	1.72E+10
0.200	1.33E+11	7.88E+10	4.35E+10	2.52E+10	1.72E+10
0.251	1.33E+11	7.88E+10	4.35E+10	2.52E+10	1.72E+10
0.316	1.33E+11	7.88E+10	4.33E+10	2.52E+10	1.72E+10
0.398	1.33E+11	7.88E+10	4.33E+10	2.52E+10	1.72E+10
0.501	1.33E+11	7.87E+10	4.33E+10	2.52E+10	1.72E+10
0.631	1.33E+11	7.87E+10	4.33E+10	2.52E+10	1.72E+10
0.794	1.33E+11	7.85E+10	4.33E+10	2.52E+10	1.72E+10
1.000	1.32E+11	7.85E+10	4.33E+10	2.50E+10	1.72E+10
1.260	1.32E+11	7.84E+10	4.32E+10	2.50E+10	1.72E+10
1.580	1.31E+11	7.81E+10	4.32E+10	2.50E+10	1.72E+10
2.000	1.30E+11	7.78E+10	4.30E+10	2.50E+10	1.72E+10
2.510	1.29E+11	7.73E+10	4.29E+10	2.49E+10	1.71E+10
3.160	1.27E+11	7.67E+10	4.28E+10	2.49E+10	1.71E+10
3.980	1.24E+11	7.58E+10	4.24E+10	2.48E+10	1.71E+10
5.010	1.20E+11	7.44E+10	4.19E+10	2.46E+10	1.69E+10
6.310	1.15E+11	7.25E+10	4.13E+10	2.43E+10	1.68E+10
7.940	1.08E+11	6.97E+10	4.03E+10	2.39E+10	1.66E+10
10.000	9.93E+10	6.60E+10	3.91E+10	2.34E+10	1.64E+10
12.600	8.86E+10	6.09E+10	3.70E+10	2.27E+10	1.60E+10
15.800	7.59E+10	5.47E+10	3.45E+10	2.16E+10	1.53E+10
20.000	6.27E+10	4.73E+10	3.12E+10	2.01E+10	1.44E+10
25.100	4.95E+10	3.92E+10	2.72E+10	1.83E+10	1.34E+10
31.600	3.71E+10	3.08E+10	2.27E+10	1.60E+10	1.19E+10
39.800	2.67E+10	2.31E+10	1.80E+10	1.32E+10	1.02E+10
50.100	1.83E+10	1.64E+10	1.34E+10	1.04E+10	8.32E+09
63.100	1.20E+10	1.10E+10	9.42E+09	7.66E+09	6.35E+09
79.400	7.45E+09	7.00E+09	6.22E+09	5.27E+09	4.54E+09
100.000	4.41E+09	4.21E+09	3.85E+09	3.41E+09	3.04E+09
126.000	2.52E+09	2.43E+09	2.27E+09	2.06E+09	1.88E+09
158.000	1.33E+09	1.29E+09	1.23E+09	1.13E+09	1.05E+09
200.000	6.16E+08	6.02E+08	5.73E+08	5.34E+08	4.96E+08
251.000	1.95E+08	1.90E+08	1.79E+08	1.61E+08	1.46E+08

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Table A4
Integral Electron Fluences (#/cm^2) Behind Solid Sphere Aluminum Shields
15-Year Worst-Case Mission (10 Years At 135W + 5 Years At 105W)
Values Do Not Include Design Margins

Degraded Energy	Shielded Electron Fluences				
	50 mils Al (1.27 mm)	100 mils Al (2.54 mm)	200 mils Al (5.08 mm)	350 mils Al (8.89 mm)	500 mils Al (12.7 mm)
> MeV	#/cm^2	#/cm^2	#/cm^2	#/cm^2	#/cm^2
0.010	3.18E+14	4.77E+13	2.33E+12	2.82E+10	1.03E+03
0.013	3.18E+14	4.77E+13	2.33E+12	2.82E+10	7.60E+03
0.016	3.18E+14	4.77E+13	2.33E+12	2.80E+10	
0.020	3.18E+14	4.77E+13	2.32E+12	2.80E+10	
0.025	3.16E+14	4.75E+13	2.31E+12	2.80E+10	6.21E+03
0.032	3.16E+14	4.74E+13	2.31E+12	2.80E+10	3.07E+03
0.040	3.14E+14	4.73E+13	2.31E+12	2.78E+10	
0.050	3.12E+14	4.69E+13	2.29E+12	2.76E+10	
0.063	3.08E+14	4.67E+13	2.29E+12	2.74E+10	
0.079	3.04E+14	4.61E+13	2.27E+12	2.72E+10	
0.100	2.98E+14	4.55E+13	2.23E+12	2.66E+10	
0.126	2.89E+14	4.46E+13	2.20E+12	2.60E+10	
0.158	2.77E+14	4.32E+13	2.16E+12	2.52E+10	
0.200	2.60E+14	4.15E+13	2.08E+12	2.41E+10	
0.251	2.38E+14	3.91E+13	1.99E+12	2.25E+10	
0.316	2.11E+14	3.60E+13	1.87E+12	2.06E+10	
0.398	1.78E+14	3.21E+13	1.71E+12	1.80E+10	
0.501	1.41E+14	2.74E+13	1.51E+12	1.47E+10	
0.631	1.05E+14	2.20E+13	1.28E+12	1.09E+10	
0.794	7.11E+13	1.63E+13	1.02E+12	6.94E+09	
1.000	4.31E+13	1.06E+13	7.49E+11	3.21E+09	
1.260	2.43E+13	5.85E+12	4.89E+11	8.21E+08	
1.580	1.14E+13	2.78E+12	2.63E+11	6.11E+07	
2.000	3.86E+12	1.25E+12	1.01E+11	4.76E+05	
2.510	1.33E+12	4.80E+11	2.08E+10		
3.160	3.80E+11	9.59E+10	5.68E+07		
3.980	4.22E+10	7.89E+08			

A-4

Table A5
Integral Electron Fluences (#/cm^2) Behind Solid Sphere Aluminum Shields
15 Year Mission (10 Years At 75W + 5 Years At 105W)
Values Do Not Include Design Margins

Degraded Energy	Shielded Electron Fluences				
	50 mils Al (1.27 mm)	100 mils Al (2.54 mm)	200 mils Al (5.08 mm)	350 mils Al (8.89 mm)	500 mils Al (12.7 mm)
> MeV	#/cm^2	#/cm^2	#/cm^2	#/cm^2	#/cm^2
0.010	2.19E+14	3.14E+13	1.39E+12	1.97E+10	1.03E+03
0.013	2.19E+14	3.14E+13	1.39E+12	1.97E+10	2.70E+03
0.016	2.19E+14	3.14E+13	1.39E+12	1.96E+10	
0.020	2.18E+14	3.14E+13	1.38E+12	1.96E+10	
0.025	2.18E+14	3.14E+13	1.38E+12	1.96E+10	
0.032	2.17E+14	3.13E+13	1.38E+12	1.95E+10	1.84E+03
0.040	2.16E+14	3.12E+13	1.38E+12	1.94E+10	
0.050	2.14E+14	3.09E+13	1.37E+12	1.93E+10	
0.063	2.12E+14	3.07E+13	1.36E+12	1.92E+10	
0.079	2.09E+14	3.04E+13	1.35E+12	1.90E+10	
0.100	2.05E+14	2.99E+13	1.34E+12	1.87E+10	
0.126	1.99E+14	2.93E+13	1.32E+12	1.82E+10	
0.158	1.90E+14	2.85E+13	1.29E+12	1.77E+10	
0.200	1.79E+14	2.72E+13	1.25E+12	1.69E+10	
0.251	1.65E+14	2.55E+13	1.19E+12	1.58E+10	
0.316	1.46E+14	2.35E+13	1.12E+12	1.44E+10	
0.398	1.23E+14	2.08E+13	1.03E+12	1.26E+10	
0.501	9.78E+13	1.76E+13	9.13E+11	1.03E+10	
0.631	7.20E+13	1.40E+13	7.78E+11	7.67E+09	
0.794	4.81E+13	1.01E+13	6.24E+11	4.76E+09	
1.000	2.85E+13	6.46E+12	4.62E+11	2.18E+09	
1.260	1.55E+13	3.46E+12	3.04E+11	5.38E+08	
1.580	6.92E+12	1.64E+12	1.68E+11	3.68E+07	
2.000	2.27E+12	7.62E+11	6.94E+10		
2.510	8.06E+11	2.97E+11	1.46E+10		
3.160	2.38E+11	6.83E+10	3.64E+07		
3.980	3.02E+10	4.44E+08			

Table A6
Total Ionizing Dose (Rads$_{Si}$) at the Center of Solid Aluminum Spheres for 15-Year Worst-Case Mission
(10 Years At 135W + 5 Years At 105W, 11 Active Years At 90% Confidence Level)
Values Do Not Include Design Margins

Aluminum Shield Thickness			Total Dose	Solar Proton Dose	Bremsstrahlung Photon Dose	Electron Dose
g/cm^2	mm	mils	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$
0.03	0.11	4.37	3.91E+08	8.26E+05	6.39E+04	3.90E+08
0.04	0.15	5.83	3.09E+08	6.44E+05	6.91E+04	3.08E+08
0.05	0.19	7.29	2.45E+08	5.37E+05	7.13E+04	2.44E+08
0.06	0.22	8.75	1.97E+08	4.54E+05	7.14E+04	1.97E+08
0.08	0.30	11.67	1.38E+08	3.54E+05	6.88E+04	1.38E+08
0.10	0.37	14.58	1.01E+08	2.88E+05	6.45E+04	1.00E+08
0.15	0.56	21.87	5.04E+07	1.96E+05	5.27E+04	5.01E+07
0.20	0.74	29.16	2.96E+07	1.51E+05	4.31E+04	2.94E+07
0.30	1.11	43.74	1.28E+07	9.98E+04	3.10E+04	1.27E+07
0.40	1.48	58.31	6.34E+06	7.50E+04	2.37E+04	6.24E+06
0.50	1.85	72.91	3.47E+06	5.73E+04	1.92E+04	3.39E+06
0.60	2.22	87.48	2.03E+06	4.78E+04	1.61E+04	1.96E+06
0.80	2.96	116.65	7.97E+05	3.40E+04	1.23E+04	7.51E+05
1.00	3.70	145.83	3.40E+05	2.59E+04	1.00E+04	3.04E+05
1.25	4.63	182.28	1.25E+05	1.99E+04	8.26E+03	9.67E+04
1.50	5.56	218.74	5.92E+04	1.57E+04	7.12E+03	3.64E+04
1.75	6.48	255.16	3.38E+04	1.27E+04	6.35E+03	1.47E+04
2.00	7.41	291.61	2.18E+04	1.07E+04	5.70E+03	5.48E+03
2.50	9.26	364.53	1.33E+04	8.02E+03	4.91E+03	4.06E+02
3.00	11.11	437.40	1.04E+04	6.15E+03	4.29E+03	3.42E+00
3.50	12.96	510.24	8.77E+03	4.92E+03	3.84E+03	
4.00	14.81	583.07	7.58E+03	4.08E+03	3.50E+03	
4.50	16.67	656.30	6.66E+03	3.42E+03	3.24E+03	
5.00	18.52	729.13	5.94E+03	2.93E+03	3.02E+03	
5.50	20.37	801.97	5.38E+03	2.53E+03	2.85E+03	
6.00	22.22	874.80	4.88E+03	2.18E+03	2.70E+03	
6.50	24.07	947.64	4.46E+03	1.93E+03	2.53E+03	
7.00	25.93	1020.87	4.15E+03	1.73E+03	2.42E+03	
7.50	27.78	1093.70	3.85E+03	1.54E+03	2.31E+03	
8.00	29.63	1166.54	3.59E+03	1.38E+03	2.21E+03	
8.50	31.48	1239.37	3.35E+03	1.25E+03	2.10E+03	
9.00	33.33	1312.20	3.13E+03	1.12E+03	2.01E+03	
9.50	35.19	1385.43	2.96E+03	1.01E+03	1.95E+03	
10.00	37.04	1458.27	2.73E+03	8.74E+02	1.86E+03	
12.50	46.30	1822.83	2.20E+03	6.38E+02	1.56E+03	
15.00	55.56	2187.40	1.77E+03	4.63E+02	1.30E+03	
20.00	74.07	2916.14	1.17E+03	2.77E+02	8.92E+02	
25.00	92.59	3645.28	8.45E+02	1.83E+02	6.62E+02	

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Aluminum Shield Thickness			Total Dose	Solar Proton Dose	Bremsstrahlung Photon Dose	Electron Dose
g/cm^2	mm	mils	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$
30.00	111.10	4374.02	5.81E+02	1.23E+02	4.58E+02	

Table A7
Total Ionizing Dose (Rads$_{Si}$) at the Center of Solid Aluminum Spheres for 15 Year Mission
(10 Years At 75W + 5 Years At 105W, 11 Active Years At 90% Confidence Level)
Values Do Not Include Design Margins

Aluminum Shield Thickness			Total Dose	Solar Proton Dose	Bremsstrahlung Photon Dose	Electron Dose
g/cm^2	mm	mils	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$	Rads$_{Si}$
0.03	0.11	4.37	3.26E+08	8.26E+05	5.45E+04	3.26E+08
0.04	0.15	5.83	2.56E+08	6.44E+05	5.84E+04	2.55E+08
0.05	0.19	7.29	2.01E+08	5.37E+05	5.98E+04	2.00E+08
0.06	0.22	8.75	1.61E+08	4.54E+05	5.97E+04	1.60E+08
0.08	0.30	11.67	1.11E+08	3.54E+05	5.71E+04	1.11E+08
0.10	0.37	14.58	8.01E+07	2.88E+05	5.31E+04	7.98E+07
0.15	0.56	21.87	3.92E+07	1.96E+05	4.31E+04	3.90E+07
0.20	0.74	29.16	2.20E+07	1.51E+05	3.49E+04	2.18E+07
0.30	1.11	43.74	8.80E+06	9.98E+04	2.47E+04	8.68E+06
0.40	1.48	58.31	4.41E+06	7.50E+04	1.88E+04	4.31E+06
0.50	1.85	72.91	2.41E+06	5.73E+04	1.52E+04	2.33E+06
0.60	2.22	87.48	1.39E+06	4.78E+04	1.27E+04	1.33E+06
0.80	2.96	116.65	5.26E+05	3.40E+04	9.68E+03	4.82E+05
1.00	3.70	145.83	2.20E+05	2.59E+04	7.88E+03	1.87E+05
1.25	4.63	182.28	8.39E+04	1.99E+04	6.49E+03	5.75E+04
1.50	5.56	218.74	4.32E+04	1.57E+04	5.58E+03	2.19E+04
1.75	6.48	255.16	2.68E+04	1.27E+04	4.94E+03	9.12E+03
2.00	7.41	291.61	1.87E+04	1.07E+04	4.45E+03	3.55E+03
2.50	9.26	364.53	1.21E+04	8.02E+03	3.80E+03	2.80E+02
3.00	11.11	437.40	9.45E+03	6.15E+03	3.30E+03	2.35E+00
3.50	12.96	510.24	7.92E+03	4.92E+03	3.00E+03	
4.00	14.81	583.07	6.82E+03	4.08E+03	2.74E+03	
4.50	16.67	656.30	5.94E+03	3.42E+03	2.52E+03	
5.00	18.52	729.13	5.27E+03	2.93E+03	2.34E+03	
5.50	20.37	801.97	4.72E+03	2.53E+03	2.20E+03	
6.00	22.22	874.80	4.26E+03	2.18E+03	2.08E+03	
6.50	24.07	947.64	3.88E+03	1.93E+03	1.95E+03	
7.00	25.93	1020.87	3.60E+03	1.73E+03	1.87E+03	
7.50	27.78	1093.70	3.31E+03	1.54E+03	1.77E+03	
8.00	29.63	1166.54	3.05E+03	1.38E+03	1.67E+03	
8.50	31.48	1239.37	2.85E+03	1.25E+03	1.60E+03	
9.00	33.33	1312.20	2.64E+03	1.12E+03	1.52E+03	
9.50	35.19	1385.43	2.47E+03	1.01E+03	1.47E+03	
10.00	37.04	1458.27	2.28E+03	8.74E+02	1.41E+03	
12.50	46.30	1822.83	1.78E+03	6.38E+02	1.14E+03	
15.00	55.56	2187.40	1.43E+03	4.63E+02	9.72E+02	
20.00	74.07	2916.14	9.75E+02	2.77E+02	6.98E+02	
25.00	92.59	3645.28	6.46E+02	1.83E+02	4.64E+02	
30.00	111.10	4374.02	4.60E+02	1.23E+02	3.37E+02	

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Table A8
Integral LET for Interplanetary Galactic Cosmic Rays (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET	LET Fluence	LET	LET Fluence
MeV*sqcm/mg	#/sqcm/day	MeV*sqcm/mg	#/sqcm/day
	Solar Minimum		Solar Maximum
1.00E-03	4.25E+05	1.00E-03	1.54E+05
1.65E-03	4.24E+05	1.65E-03	1.54E+05
1.69E-03	3.29E+05	1.69E-03	1.07E+05
1.70E-03	3.04E+05	1.70E-03	9.42E+04
1.72E-03	2.84E+05	1.72E-03	8.46E+04
1.77E-03	2.54E+05	1.77E-03	7.02E+04
1.81E-03	2.30E+05	1.81E-03	5.98E+04
1.85E-03	2.12E+05	1.85E-03	5.20E+04
1.91E-03	1.90E+05	1.91E-03	4.34E+04
1.98E-03	1.72E+05	1.98E-03	3.75E+04
2.01E-03	1.67E+05	2.01E-03	3.59E+04
2.13E-03	1.46E+05	2.13E-03	3.05E+04
2.28E-03	1.27E+05	2.28E-03	2.69E+04
2.53E-03	1.07E+05	2.53E-03	2.39E+04
3.01E-03	8.29E+04	3.01E-03	2.11E+04
3.54E-03	6.87E+04	3.54E-03	1.98E+04
4.52E-03	5.55E+04	4.52E-03	1.88E+04
5.56E-03	4.90E+04	5.56E-03	1.83E+04
6.54E-03	4.58E+04	6.54E-03	1.82E+04
7.52E-03	2.76E+04	7.52E-03	7.46E+03
8.55E-03	2.13E+04	8.55E-03	5.04E+03
9.60E-03	1.75E+04	9.60E-03	3.97E+03
1.97E-02	7.02E+03	1.97E-02	1.88E+03
2.96E-02	5.07E+03	2.96E-02	1.63E+03
4.00E-02	4.33E+03	4.00E-02	1.55E+03
5.04E-02	3.81E+03	5.04E-02	1.43E+03
6.00E-02	3.50E+03	6.00E-02	1.36E+03
6.97E-02	2.91E+03	6.97E-02	1.08E+03
8.01E-02	2.66E+03	8.01E-02	1.01E+03
9.00E-02	2.40E+03	9.00E-02	9.12E+02
1.01E-01	2.23E+03	1.01E-01	8.74E+02
2.00E-01	9.84E+02	2.00E-01	3.59E+02
4.02E-01	4.33E+02	4.02E-01	1.52E+02

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Table A8 (Continued)
Integral LET for Interplanetary Galactic Cosmic Rays (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET	LET Fluence	LET	LET Fluence
MeV*sqcm/mg	#/sqcm/day	MeV*sqcm/mg	#/sqcm/day
	Solar Minimum		Solar Maximum
6.03E-01	2.90E+02	6.03E-01	1.10E+02
7.96E-01	2.23E+02	7.96E-01	8.84E+01
1.00E+00	1.79E+02	1.00E+00	7.22E+01
2.01E+00	3.39E+01	2.01E+00	5.88E+00
3.02E+00	1.43E+01	3.02E+00	2.03E+00
3.99E+00	7.76E+00	3.99E+00	1.02E+00
5.03E+00	4.59E+00	5.03E+00	5.81E-01
5.99E+00	3.07E+00	5.99E+00	3.80E-01
8.00E+00	1.55E+00	8.00E+00	1.90E-01
1.01E+01	9.00E-01	1.01E+01	1.10E-01
1.11E+01	7.17E-01	1.11E+01	8.75E-02
1.20E+01	5.76E-01	1.20E+01	7.04E-02
1.30E+01	4.67E-01	1.30E+01	5.71E-02
1.40E+01	3.85E-01	1.40E+01	4.72E-02
1.50E+01	3.16E-01	1.50E+01	3.88E-02
1.60E+01	2.61E-01	1.60E+01	3.20E-02
1.70E+01	2.20E-01	1.70E+01	2.71E-02
1.80E+01	1.85E-01	1.80E+01	2.27E-02
1.91E+01	1.54E-01	1.91E+01	1.89E-02
2.00E+01	1.30E-01	2.00E+01	1.60E-02
2.49E+01	4.45E-02	2.49E+01	5.50E-03
3.00E+01	6.27E-04	3.00E+01	8.18E-05
3.49E+01	6.86E-05	3.49E+01	1.06E-05
4.01E+01	4.18E-05	4.01E+01	6.50E-06
4.50E+01	2.83E-05	4.50E+01	4.42E-06
5.00E+01	2.00E-05	5.00E+01	3.13E-06
5.06E+01	1.92E-05	5.06E+01	3.00E-06
5.55E+01	1.34E-05	5.55E+01	2.11E-06
6.02E+01	9.38E-06	6.02E+01	1.49E-06
6.53E+01	6.32E-06	6.53E+01	1.01E-06
7.00E+01	4.40E-06	7.00E+01	7.01E-07
7.50E+01	2.83E-06	7.50E+01	4.52E-07
8.04E+01	1.65E-06	8.04E+01	2.63E-07
8.52E+01	7.71E-07	8.52E+01	1.23E-07
9.03E+01	1.94E-07	9.03E+01	3.10E-08
9.57E+01	2.88E-08	9.57E+01	4.60E-09
1.00E+02	1.19E-08	1.00E+02	1.89E-09
1.01E+02	5.27E-09	1.01E+02	8.41E-10
1.03E+02	2.54E-09	1.03E+02	4.05E-10

Table A9
Integral LET for the October 1989 Solar Particle Event (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET	LET Fluence	LET Fluence	LET Fluence
MeV*cm^2/mg	#/cm^2/s	#/cm^2/s	#/cm^2/s
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
1.00E-03	1.93E+05	5.21E+04	1.15E+04
2.01E-03	1.93E+05	5.21E+04	1.15E+04
3.01E-03	1.93E+05	5.20E+04	1.14E+04
4.02E-03	1.92E+05	5.17E+04	1.13E+04
5.01E-03	1.90E+05	5.11E+04	1.11E+04
6.03E-03	1.86E+05	5.02E+04	1.08E+04
7.02E-03	1.82E+05	4.90E+04	1.05E+04
7.97E-03	1.77E+05	4.76E+04	1.01E+04
8.95E-03	1.71E+05	4.60E+04	9.68E+03
1.01E-02	1.64E+05	4.40E+04	9.19E+03
1.99E-02	9.60E+04	2.55E+04	5.07E+03
2.99E-02	5.39E+04	1.43E+04	2.78E+03
4.00E-02	3.23E+04	8.56E+03	1.65E+03
4.98E-02	2.11E+04	5.59E+03	1.07E+03
6.00E-02	1.45E+04	3.84E+03	7.33E+02
6.97E-02	1.06E+04	2.81E+03	5.34E+02
8.01E-02	7.91E+03	2.09E+03	3.96E+02
9.00E-02	6.16E+03	1.63E+03	3.08E+02
9.99E-02	4.90E+03	1.29E+03	2.44E+02
2.00E-01	9.50E+02	2.51E+02	4.67E+01
3.01E-01	3.15E+02	8.31E+01	1.53E+01
4.02E-01	1.25E+02	3.32E+01	6.08E+00
5.01E-01	3.82E+01	1.01E+01	1.80E+00
6.03E-01	1.86E+01	4.94E+00	8.78E-01
7.01E-01	1.35E+01	3.58E+00	6.52E-01
8.05E-01	9.85E+00	2.62E+00	4.91E-01
9.04E-01	7.55E+00	2.02E+00	3.87E-01
1.00E+00	5.88E+00	1.57E+00	3.10E-01
2.01E+00	7.49E-01	2.06E-01	5.99E-02
3.02E+00	4.11E-01	1.13E-01	3.33E-02
3.99E+00	2.64E-01	7.29E-02	2.14E-02
5.03E+00	1.74E-01	4.80E-02	1.42E-02
6.06E+00	1.21E-01	3.36E-02	9.92E-03
7.04E+00	8.68E-02	2.40E-02	7.11E-03
8.00E+00	6.39E-02	1.77E-02	5.26E-03
8.99E+00	5.04E-02	1.40E-02	4.13E-03
1.01E+01	3.85E-02	1.07E-02	3.15E-03
2.00E+01	5.75E-03	1.60E-03	4.63E-04
2.52E+01	2.14E-03	5.95E-04	1.72E-04

Table A9 (Continued)
Integral LET for the October 1989 Solar Particle Event (Z=1-92)
100 mils Aluminum Shielding
Values Do Not Include Design Margins

LET	LET Fluence	LET Fluence	LET Fluence
MeV*cm^2/mg	#/cm^2/s	#/cm^2/s	#/cm^2/s
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
3.00E+01	1.83E-05	5.10E-06	1.55E-06
3.53E+01	7.23E-07	2.01E-07	7.14E-08
4.01E+01	3.26E-07	9.08E-08	3.43E-08
4.50E+01	1.95E-07	5.44E-08	2.12E-08
5.00E+01	1.36E-07	3.78E-08	1.48E-08
5.55E+01	8.43E-08	2.35E-08	9.31E-09
6.02E+01	4.92E-08	1.37E-08	5.58E-09
6.53E+01	3.28E-08	9.12E-09	3.75E-09
7.00E+01	2.49E-08	6.92E-09	2.84E-09
7.50E+01	1.80E-08	5.00E-09	2.04E-09
8.04E+01	1.20E-08	3.34E-09	1.36E-09
8.52E+01	6.69E-09	1.86E-09	7.56E-10
9.03E+01	2.03E-09	5.64E-10	2.29E-10
9.46E+01	1.33E-10	3.71E-11	1.51E-11
1.00E+02	5.01E-11	1.39E-11	5.66E-12
1.01E+02	2.22E-11	6.19E-12	2.51E-12
1.03E+02	1.07E-11	2.99E-12	1.21E-12

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Table A10
Differential Fluxes from Solar Proton Events
100 mils Aluminum Shielding, CREME96
Note: Spectra were cut off at E =1 MeV and E=1000 MeV
Values Do Not Include Design Margins

Energy	Proton Flux	Proton Flux	Proton Flux
MeV	$\#/cm^2/s$	$\#/cm^2/s$	$\#/cm^2/s$
	Average Over Peak	Average Over Worst Day	Average Over Worst Week
1.00	1.75E+03	4.62E+02	8.85E+01
2.00	2.68E+03	7.09E+02	1.36E+02
3.02	3.47E+03	9.17E+02	1.76E+02
4.04	4.11E+03	1.09E+03	2.09E+02
5.04	4.62E+03	1.22E+03	2.36E+02
6.03	5.03E+03	1.33E+03	2.58E+02
7.02	5.33E+03	1.41E+03	2.75E+02
8.06	5.56E+03	1.47E+03	2.88E+02
9.00	5.69E+03	1.51E+03	2.96E+02
10.05	5.76E+03	1.53E+03	3.01E+02
14.99	5.41E+03	1.44E+03	2.92E+02
20.03	4.50E+03	1.21E+03	2.52E+02
24.98	3.57E+03	9.65E+02	2.07E+02
30.31	2.73E+03	7.40E+02	1.64E+02
35.27	2.11E+03	5.75E+02	1.31E+02
40.49	1.61E+03	4.42E+02	1.04E+02
50.50	9.91E+02	2.73E+02	6.79E+01
60.43	6.33E+02	1.75E+02	4.58E+01
70.33	4.20E+02	1.17E+02	3.20E+01
79.63	2.94E+02	8.18E+01	2.33E+01
90.17	2.03E+02	5.65E+01	1.68E+01
100.69	1.44E+02	4.01E+01	1.24E+01
150.25	3.84E+01	1.06E+01	3.80E+00
200.77	1.39E+01	3.79E+00	1.50E+00
299.59	3.32E+00	8.62E-01	3.88E-01
400.31	1.16E+00	2.85E-01	1.39E-01
499.23	4.97E-01	1.16E-01	5.96E-02
605.64	2.07E-01	4.64E-02	2.54E-02
704.94	1.10E-01	2.48E-02	1.44E-02
798.17	6.61E-02	1.48E-02	9.03E-03
903.74	3.95E-02	8.88E-03	5.66E-03
995.41	2.65E-02	5.96E-03	3.94E-03

Glossary

Linear Energy Transfer (LET) - a measure of the energy deposited per unit path length as an energetic particle travels through a material. The common LET unit is MeV-cm^2/mg of material (Si for MOS devices, etc.).

Multiple Bit Upset (MBU) - an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.

Single Event Burnout (SEB) - a condition that can cause device destruction due to a high current state in a power transistor.

Single Event Dielectric Rupture (SEDR) – a single-event effect in antifuse-type field programmable gate arrays that may result destruction of the dielectric and functional failure of the cell.

Single Event Effect (SEE) - any measurable effect to a circuit due to a strike by a single ion. Such effects include (but are not limited to) SEUs, SHEs, SELs, SEBs and SEGRs.

Single Event Gate Rupture (SEGR) - a single ion induced condition in power MOSFETs that may result in the formation of a conducting path in the gate oxide.

Single Event Latchup (SEL) - a condition that causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.

Single Event Upset (SEU) - a permanent or transient change of state induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are "soft" errors in that a reset or rewriting of the device causes normal device behavior thereafter.

Single Hard Error (SHE) - an SEU that causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.

Threshold LET (LET$_{th}$) - the minimum LET to cause an effect at a particle fluence of 1×10^7 ions/cm^2.

Total Ionizing Dose (TID) - the mean energy imparted by ionizing radiation to a sensitive device region divided by the mass of the region. This is typically given in units of rad(Si), where 1 rad(Si) = 100 erg deposited per gram of silicon.